Achievable Rates Comparison for Phase-Conjugated Twin-Waves and PM-QPSK

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Abstract: *Phase-conjugated twin-waves (PCTW)-QPSK is experimentally compared to PM-QPSK in terms of achievable information rate for bit-wise decoders. For typical long-haul transmission distances, PM-QPSK with soft-decision FEC achieves significantly higher spectral efficiency than PCTW-QPSK.*

Keywords: *Coherent communication, nonlinear mitigation, achievable information rate, phase conjugated twin waves.*

I. Introduction

Coherent optical communication systems, as designed today, are limited in terms of transmission reach by Kerr nonlinearities. Different techniques for mitigation of the deterministic nonlinear distortion have been suggested such as digital back-propagation [1], mid-span spectral inversion [2], coherent superposition in phase sensitive amplification techniques [3], the nonlinear Fourier transform [4], and exploiting four-dimensional channel distributions in the receiver [5]. Another method, which is the topic of this paper, is the phase-conjugated twin-waves (PCTW) transmission scheme [6]. This method transmits a phase-conjugated copy of a constellation on, for instance, orthogonal polarizations [6] or different wavelengths [7]. The nonlinear distortion can then be compensated by adding the signal and conjugate using all-optical techniques [3] or in the digital signal processing (DSP) after detection [7]. When the signal and conjugated copy are transmitted in orthogonal polarizations, this method is equivalent to transmitting real-valued signals, such as PM-BPSK, where the nonlinear interference is squeezed during transmission [6]. Many of the experimental investigations of PCTW optimize the channel for the PCTW scheme, by for instance using in-line dispersion compensation [3] or fibers with low chromatic dispersion [6] [7], to enhance the nonlinearities, and compare it to a conventional modulation scheme such as PM-QPSK, over the same link. However, these types of channels are then typically far from optimized for a conventional modulation scheme.

In this paper we compare a single-channel 28 Gbaud PCTW-QPSK to a 28 Gbaud PM-QPSK system in a realistic upgrade scenario, i.e. no inline dispersion compensation is used and the dispersion map is optimized separately in the two cases by changing the pre- and post-dispersion compensation. We assume soft-decision decoding and compare the two systems in terms of achievable information rate (AIR) using generalized mutual information (GMI) [8]. It is found that for typical long-haul distances (< 20,000 km), PM-QPSK and a strong code achieves a significantly higher spectral efficiency than PCTW-QPSK. However, for extremely long transmission links, where conventional receiver algorithms tend to fail for PM-QPSK, the twin-waves approach could be an interesting alternative.

II. Phase-Conjugated Twin-Waves and Achievable Information Rates

The constellation for conventional PM-QPSK can be written as $\left\{\left[s_x, s_y\right]^T\right\}$, where $s_x = \{(\pm 1 \pm i)/2\}$ and $s_y = \{(\pm 1 \pm i)/2\}$. For PCTW-QPSK, the signal in the y-polarization is a conjugated copy of the signal in the x-polarization giving the symbols $\left\{\left[s_x, s_y = s_x^*\right]^T\right\}$, where s_x is still a QPSK constellation. By applying a polarization rotation, using one of the Jones matrices

$$J_1 = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ -i & i\end{bmatrix}, \qquad J_2 = \frac{1}{2}\begin{bmatrix}1-i & 1+i\\ 1+i & 1-i\end{bmatrix},$$

to the PCTW-QPSK symbol alphabet, the different representations shown in Fig. 1 can be obtained. Applying J_1, the PM-BPSK representation given by $\{[\pm 1, \pm 1]^T/\sqrt{2}\}$ is found [6], which is the representation used in our experimental realization. If J_2 is applied, PCTW-QPSK can be interpreted as polarization-switched (PS)-BPSK with the constellation $\{[\pm 1, 0]^T, [0, \pm 1]^T\}$. This representation is used in the DSP algorithms implemented for PCTW-QPSK in this paper.

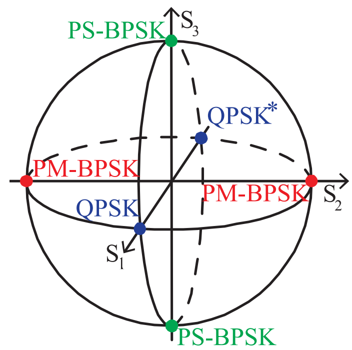

Fig. 1 - Poincaré-sphere representation of different interpretations of PCTW-QPSK.

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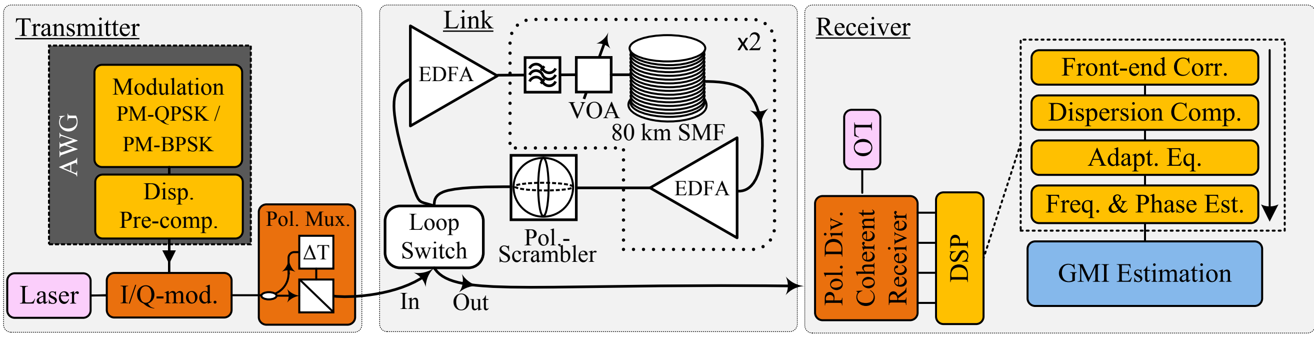

Fig. 2 - Experimental setup.

With todays' optical communication systems relying on sophisticated soft-decision forward-error correction (FEC) schemes, a relevant system figure-of-merit is the AIR estimated with either mutual information (MI) or GMI, depending on the FEC scheme that is intended to be used. It is important to note that for a known channel transition distribution, the PCTW-QPSK can never obtain a higher MI than PM-QPSK. The reason for this is that PCTW-QPSK is a subset of the PM-QPSK symbol alphabet. However, for the nonlinear fiber optical system the true channel transition distribution is not known. Typically, the concept of mismatched decoding is applied [9], which means that the received samples are decoded as if they were transmitted over a known auxiliary channel. This auxiliary channel is often assumed to be an additive white Gaussian noise channel with the same variance in all dimensions, which is the assumption in this paper and also in many realistic decoders.

The GMI and the log-likelihood ratios (LLRs) calculated for N received symbols are

$$\mathrm{GMI} \approx m - \frac{1}{N}\sum_{k=1}^{m}\sum_{i=1}^{N}\log_2\left(1+\exp\left((-1)^{b_{k,i}}LLR_{k,i}\right)\right), \qquad LLR_{k,i} = \log\frac{\sum_{s\in\mathcal{X}_{k,1}}\exp\left(-\frac{1}{N_0}\|y_i-s\|^2\right)}{\sum_{s\in\mathcal{X}_{k,0}}\exp\left(-\frac{1}{N_0}\|y_i-s\|^2\right)},$$

where $b_{k,i}$ is the transmitted bit sequence, $\mathbf{y}$ is the received symbol and $\boldsymbol{s}$ denotes a symbol from the constellation $\mathcal{X}$ with cardinality 2^m. The index i denotes the i^{th} transmitted symbol and the index k the bit position [8]. Note that the GMI depends on the bit-to-symbol mapping and that we use Gray-mapping of the QPSK constellation. The GMI is normalized to two-dimensional (2D) symbols, i.e. PM-QPSK has a maximum GMI of 2 bit/2D-symbol and PCTW-QPSK a maximum GMI of 1 bit/2D-symbol. The GMI gives a good estimate of the post-FEC bit error rate (BER) for systems relying on bit-wise decoding, which is the case for many state-of-the-art FEC solutions for optical communication [8].

III. System and Experimental Description

The efficiency of the nonlinear mitigation for a PCTW system is determined by the design parameters of the transmission link such as power map, dispersion map, amplifier spacing, fiber type, etc. In this paper we investigate the suitability of PCTW in links that are typical for coherent PM-QPSK today, i.e., without inline dispersion compensation or Raman amplification. The available dispersion compensation is limited to pre-dispersion compensation on the transmitter side and post-dispersion compensation in the receiver, both done electronically. In this paper we investigate single channel transmission, but it should be noted that for WDM transmission the gains seen by PCTW are typically smaller, unless the phase conjugation can be applied over the full WDM spectra which is difficult [10].

The experimental setup is shown in Fig. 2. The transmitter is based on an arbitrary waveform generator (AWG) for electrical signal generation. Since PCTW-QPSK and PM-BPSK are equivalent for single-channel transmission, as explained in Section II, we implement the PCTW-QPSK scheme using PM-BPSK. We generate either 28 Gbaud PM-QPSK or 28 Gbaud PCTW-QPSK. When applicable, pre-dispersion compensation is applied in the AWG. Polarization multiplexing is emulated using a split and de-correlate stage. The signals are propagated over a recirculating loop consisting of two spans of 80 km standard single-mode fiber (SMF). Two erbium-doped fiber amplifiers (EDFAs) compensate the loss of the spans and a loop-synchronized polarization scrambler is used to avoid any nonrealistic accumulation of polarization effects. A third EDFA is used to compensate for the loss of the polarization scrambler and the loop switching components. The signal is detected using a coherent receiver and sampled by a four-channel oscilloscope with 50 GS/s sampling rate. In the digital domain, optical front-end correction is applied before dispersion compensation in the frequency domain is carried out. For PM-QPSK, a conventional DSP structure is used in which adaptive equalization and polarization demultiplexing is carried out by the constant modulus algorithm (CMA) and phase tracking is done with the Viterbi-Viterbi algorithm. The only DSP difference for PCTW-QPSK is that a modified CMA is used to enable polarization demultiplexing of the signals [11]. After the DSP, the AIR is estimated using GMI [8].

IV. Results and Discussion

The attainable transmission distances for PCTW-QPSK at 20% FEC overhead, i.e. at an AIR of 1/1.2 = 0.83 bit/2D-symbol, as a function of launch power with different dispersion maps are shown in Fig. 3(a). For 0% and 100% pre-dispersion compensation, the optimal launch power is −1 dBm. The longest reach is obtained by a symmetrical dispersion map, i.e. 50% pre-dispersion compensation, which also increases the optimal launch power to 0 dBm. The transmission reach for 32% and 64% pre-dispersion compensation is shorter than that of 50% but longer than that obtained by 0% or 100%. For PM-QPSK there is no significant difference with regard to the dispersion maps, which can be seen in Fig. 3(b) where the plots for all the different dispersion maps are indistinguishable. For PM-QPSK (not plotted) the transmission

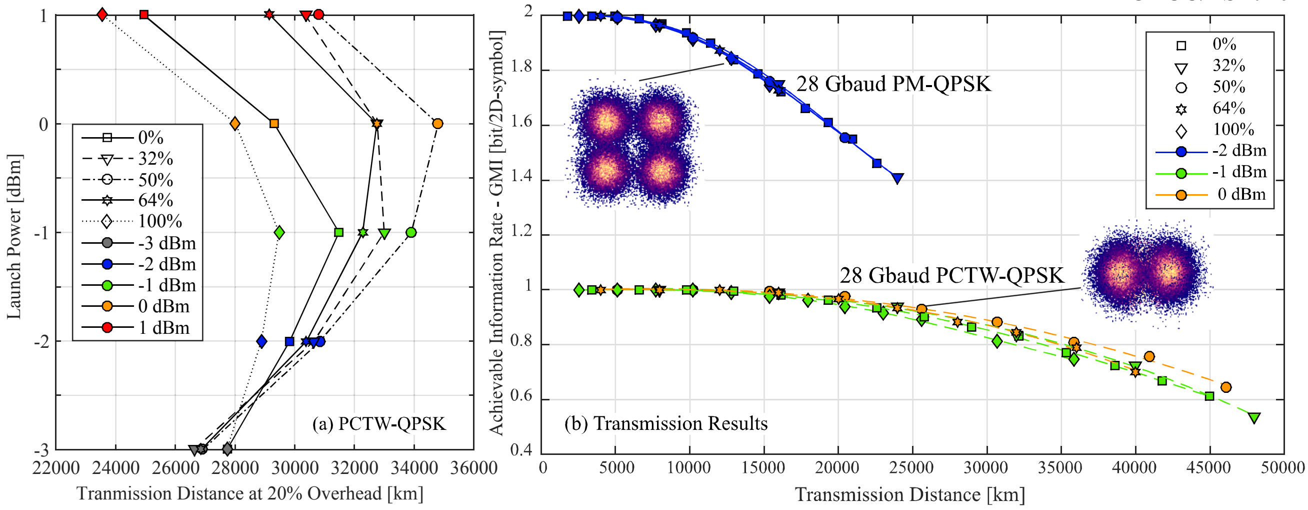

Fig. 3 – (a) Transmission distance for 28 Gbaud PCTW-QPSK at 20% FEC overhead for different launch powers and different amounts of dispersion pre-compensation. (b) Achievable information rate as a function of transmission distance using optimal launch power for each dispersion map for 28 Gbaud PM-QPSK and 28 Gbaud PCTW-QPSK. Note that for PM-QPSK, the differences between the curves for different dispersion maps are indistinguishable.

reach is approximately the same for −2 dBm and −1 dBm for all dispersion maps. This means that for PCTW-QPSK with a symmetric dispersion map, the optimal launch power is increased by roughly 1 to 2 dB over PM-QPSK.

In Fig. 3(b), the AIR, calculated using GMI, is plotted as a function of transmission distance for the optimal launch power for each scenario. Note that for PM-QPSK, the results for −1 dBm are very similar to those of −2 dBm but only the latter is plotted for clarity. PM-QPSK can be transmitted over slightly more than 20,000 km before the implemented DSP becomes unreliable. Note that we have removed measurement points where the DSP did not converge or phase-slips occurred in the phase tracking. As seen, for all transmission distances that the DSP for PM-QPSK can handle, PM-QPSK has a significantly higher AIR compared to PCTW-QPSK. Therefore, for these transmission distances, there is a clear loss in spectral efficiency by using PCTW-QPSK instead of decreasing the rate of the code that is used in combination with PM-QPSK. It is only for distances larger than 20,000 km, PCTW-QPSK is an interesting alternative since it can relax the requirements on the DSP. Note however, that if more noise-tolerant DSP algorithms are used and cycle slip mitigation is implemented, it should be possible to increase the distance over which PM-QPSK can be transmitted. For distances larger than 20,000 km, other modulation formats with increased sensitivity over PM-QPSK but with higher spectral efficiency than PCTW-QPSK, such as PS-QPSK [12], could also be an interesting alternative.

V. Conclusions

Although the phase-conjugated twin-wave approach has recently attracted a lot of attention for its capability to increase the distance significantly when compared at a fixed pre-FEC BER, we show that for typical long-haul transmission distances (<20,000 km), 28 Gbaud PM-QPSK outperforms 28 Gbaud PCTW-QPSK in terms of the achievable information rate. This means that for systems using soft-decision coding schemes with high overheads, PM-QPSK is a more spectrally-efficient solution. However, PCTW-QPSK could find niche applications such as low-complexity systems using hard-decision FEC schemes or systems where extreme transmission distances are required.

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